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Characterization of a High-Power, High-Frequency, Soft-Switching Power Converter for EMC Considerations

Measurement Final Report

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INTRODUCTION

The Office of Naval Research (ONR) Power Electronics Building Block (PEBB) program is developing power electronics for advanced shipboard electric power distribution systems. An essential element of the PEBB is the control and monitoring circuitry that enables “smart power.” Integration of the control circuitry into a common substrate with a power switching device such as an Insulated Gate Bipolar Transistor (IGBT) or Metal-Oxide Semiconductor (MOS)-Controlled Thyristor (MCT) should improve system performance. This effort should lead to increased reliability, and reduced cost, size, and weight.

Bringing together low-power control circuitry and high-power switching circuitry into a common substrate or restricted volume will raise the possibility of electromagnetic interference (EMI). The installation of the high-power and high-switching-speed PEBB devices in a shipboard environment will also increase the possibility of conducted EMI in the shipboard power distribution system. The collocation of the sensitive PEBB devices with other high-power radio frequency (RF) communication and radar systems will also raise radiated EMI issues. Space and Navayl Warfare Systems Center, San Diego (SSC San Diego) was funded to address the important issue of determining the acceptable radiated emission and susceptibility levels for PEBB modules, power inverters and converters, and other shipboard RF equipment. This effort started in May 1997.

This research has been directed toward evaluation of the radiated emissions of high-power devices. PEBB modules have not been available for testing by SSC San Diego. Instead, a commercial hard-switching motor controller was provided in November 1998, and a soft-switching direct current (DC) converter developed under an ONR Dual-Use Applications Program was provided in August 2000. The radiated emissions of these units have been measured using the SSC San Diego Gigahertz Transverse Electromagnetic (GTEM) cell. This report describes the results of the soft-switching DC converter tests.

OBJECTIVE

The long-term objective of this research is to characterize PEBBs in terms of electromagnetic compatibility (EMC) for use in existing and advanced shipboard electric power systems. Radiated emissions and susceptibility levels will be studied. EMI suppression techniques in large and small high-density power electronic modules will be developed.

Because PEBBs have been in high demand for other developmental and test purposes, PEBBs have not been available for EMI testing by SSC San Diego personnel. In the meantime, the radiated emissions of L3 Communications Power Systems Group's PCM-3 DC-to-DC power converter (developed under the ONR DUST program) was tested at the SSC San Diego GTEM facility. The emissions of this soft-switching prototype unit can be used as a baseline against which later PEBB units may be compared.

This report presents the setup, experimental techniques, and results of the radiated emissions tests on the PCM-3 soft-switching power converter using the GTEM facility. Radiated emissions data obtained in a shielded enclosure at L3 Communications Power Systems Group (PSG) facilities are also presented for comparison.

EMI MEASUREMENT DESCRIPTION

The SSC San Diego EMI measurement facilities include a GTEM cell, a high-voltage DC power supply, a water cooling system, filters for power lines, oscilloscopes, spectrum analyzers, and an alternating current (AC) load bank. A 50-kW, high-voltage DC load bank was required for this test.

The equipment under test was L-3 Communications Power Systems Group's PCM-3 DC-to-DC power converter. The PCM-3 uses a soft-switched resonant bridge with an auxiliary resonant commutated pole (ARCP) topology. With a soft-switching frequency of 16.25 kHz, it converts a DC input voltage of up to 800 volts to an output voltage of up to 270 volts DC, and weighs about 850 pounds. The unit is a prototype, and currently uses conventional, insulated gate bipolar transistors (IGBTs) for its switches. Future versions will incorporate the PEBB IGBT or MCT switches and will have enhanced packaging. Figure 1 shows the PCM-3 unit inside the GTEM cell.

Figure 1. PCM-3 hooked up inside GTEM cell.

Figure 2 shows the setup that was used for testing the PCM-3's radiated emissions. The PCM-3 DC-to-DC voltage converter was placed inside the GTEM cell. The Dynapower Corporation DC power supply provided a variable input voltage to the PCM-3 unit. A high-voltage resistive load bank, rented from Hawthorne Power Systems, provided a variable output load. Engineers from L-3 Communications Power Systems Group controlled and monitored operation of the PCM-3 unit from outside the GTEM cell. The power, control, and monitoring lines passed through a shielded opening on the side of the GTEM cell. As the PCM-3 unit was exercised under various input voltage and output load conditions, its radiated emissions were measured using a Hewlett-Packard ESA-series spectrum analyzer.

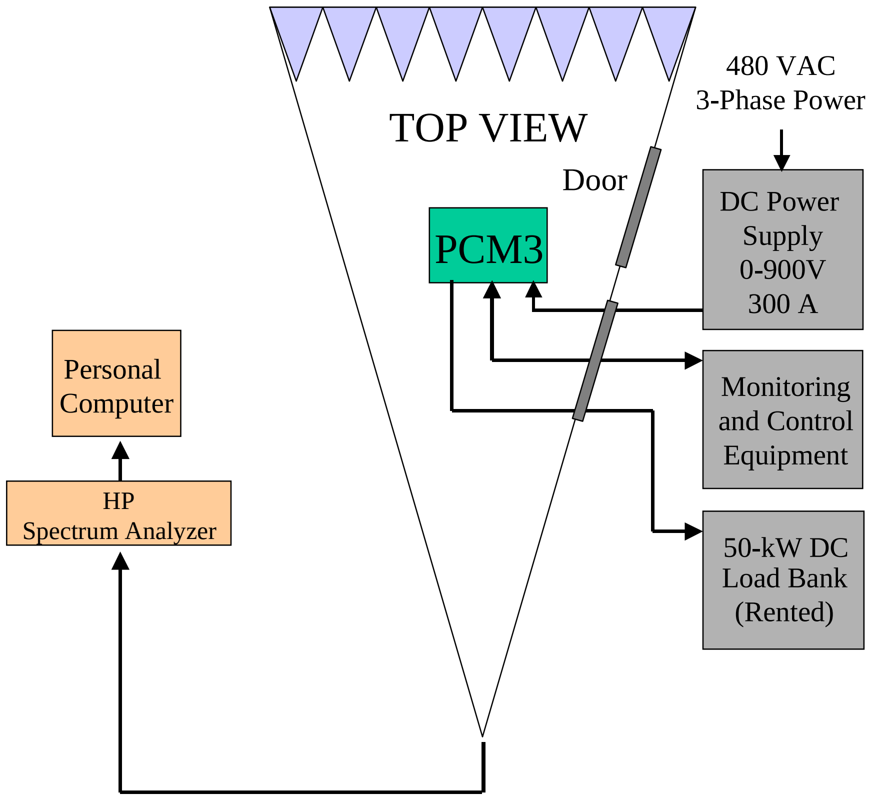

Figure 2. Test setup for PCM-3 radiated emissions using GTEM cell.

Figure 3 shows the EMCO Model 5317 GTEM cell. This device can be used for radiated emissions (RE) tests in the 9-kHz to 5-GHz frequency range, or radiated interference (RI) (susceptibility) tests in the DC to 20-GHz range. The radiated emissions tests are conducted by placing the equipment under test (EUT) in the GTEM cell and operating the equipment in some predetermined mode. The voltage measured at the GTEM output is related to the radiated field emitted by the EUT by the following equation, as derived in the appendix:

$$E_i = 10 \text{ V } f_{GHz} .$$

Figure 4 shows the DC load bank that was rented for these tests. This unit has switchable resistive loads that allowed testing the PCM-3 under various load conditions.

Figure 3. EMCO Model 5317 GTEM cell.

Figure 4. Hawthorne power DC load bank.

Figure 5 shows the DC power supply purchased from Dynapower Corporation. For these tests, this unit supplied between 200 and 750 VDC to the PCM-3 converter. Figure 6 shows L-3 Power Systems Group's monitoring equipment located outside the GTEM cell.

Figure 5. DC power supply.

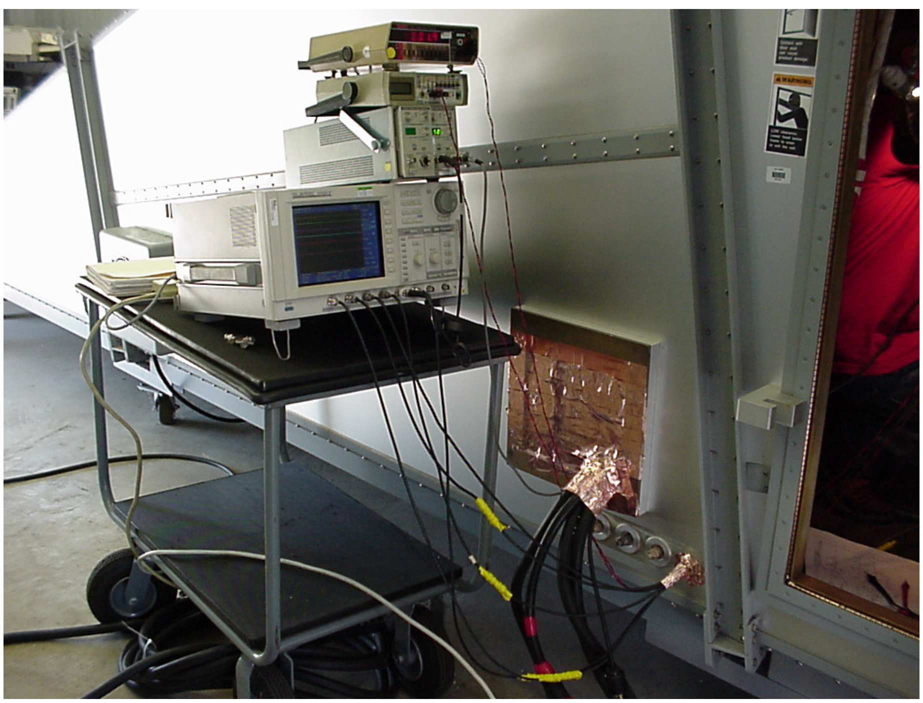

Figure 6. Monitoring equipment.

Figure 7 shows the GTEM laboratory's measurement equipment, including spectrum analyzer and digital oscilloscope. Figure 8 shows an L-3 Power Systems Group engineer monitoring the PCM-3 operation. The figure shows the overall laboratory layout with GTEM cell, monitoring equipment, power supply, and load bank.

Figure 7. GTEM measurement equipment.

Figure 8. Monitoring PCM-3 operation.

Figure 9 shows sample set of traces from the monitoring equipment is shown in Figure 9. Table 1 shows the meaning of the various traces.

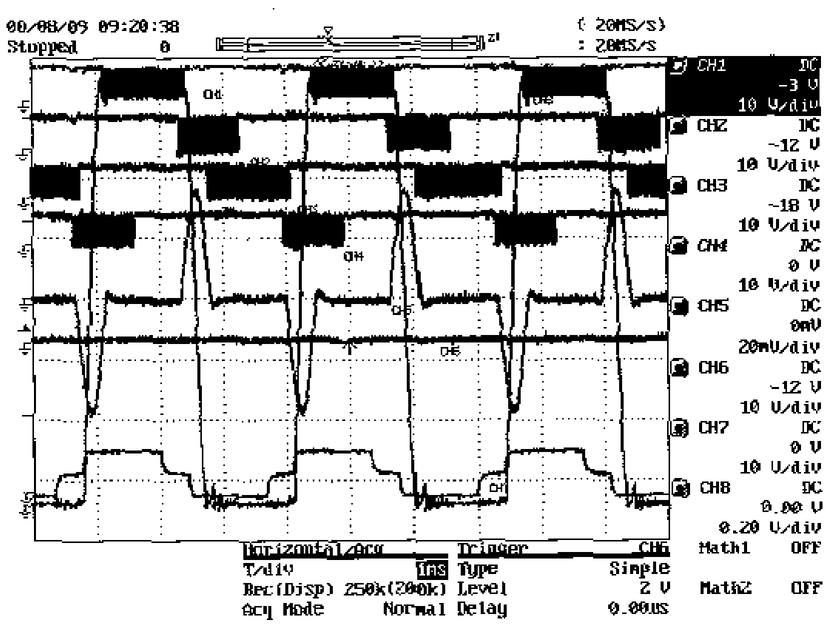

Figure 9. PCM-3 monitoring traces.

Table 1. Trace descriptions for figure 9.

Channel	Description
1	Lower Switch #1 (LS1) Voltage
2	Upper Commutation Switch #1 (UCS1) Voltage
3	Upper Switch #1 (US1) Voltage
4	Lower Commutation Switch #1 (LCS1) Voltage
5	Commutation Current Side #1
6	Power Up Reset Signal
7	Commutation Voltage Side #1
8	V_{CE} across Upper Switch #1

MEASUREMENT RESULTS

The PCM-3 was operated under various input voltage and output load conditions inside the GTEM cell. The radiated emissions in the GTEM produced a voltage across the feedpoint of the cell, which was measured as power versus frequency using a spectrum analyzer. These data may be related to field strength to compare with radiated emissions limits as described in MIL-STD-461.

Figure 10 shows how the spectrum analyzer data are operated upon to obtain the electric field strength data. The measured spectrum analyzer data (power, *P*, in dBm versus frequency) is converted to a voltage, *V*, versus frequency spectrum. This waveform is then multiplied by the GTEM transfer function (see appendix) to obtain the electric field intensity versus frequency. The measurement bandwidth of the spectrum analyzer (10 kHz) must be considered in calculating the amplitude of the electric field intensity.

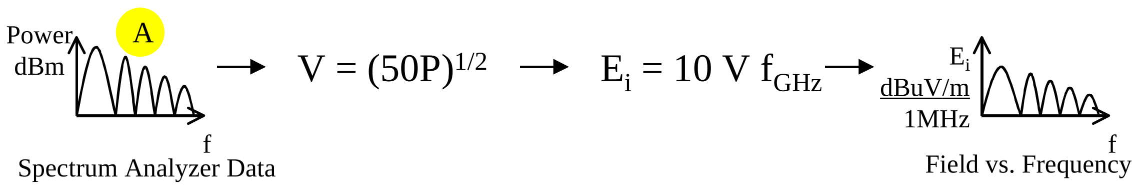

Figure 10. Determination of electric field from spectrum analyzer data.

Electrical equipment to be used by the U.S. Navy is subject to the MIL-STD-461 limitations. Other commercial standards may apply, depending on the equipment's intended use. The radiated emissions limit specified by MIL-STD-461D has been superimposed on the graphs of the measured electric fields in figures 11 through 22. In several of the early measurements, the spectrum analyzer's upper frequency was set to 1 MHz. As testing continued, we realized that the emissions were low at the frequencies below a few megahertz, so we increased this frequency to 20 MHz.

The emissions are highest around 4, 8, 16, 20, and 24 MHz. The emissions did not change much with variations in the input voltage or the load current. A separate measurement was made with only the low-voltage control logic turned on, no high-voltage operation. This plot (figure 23) shows that the control logic caused the spikes at 8 and 16 MHz.

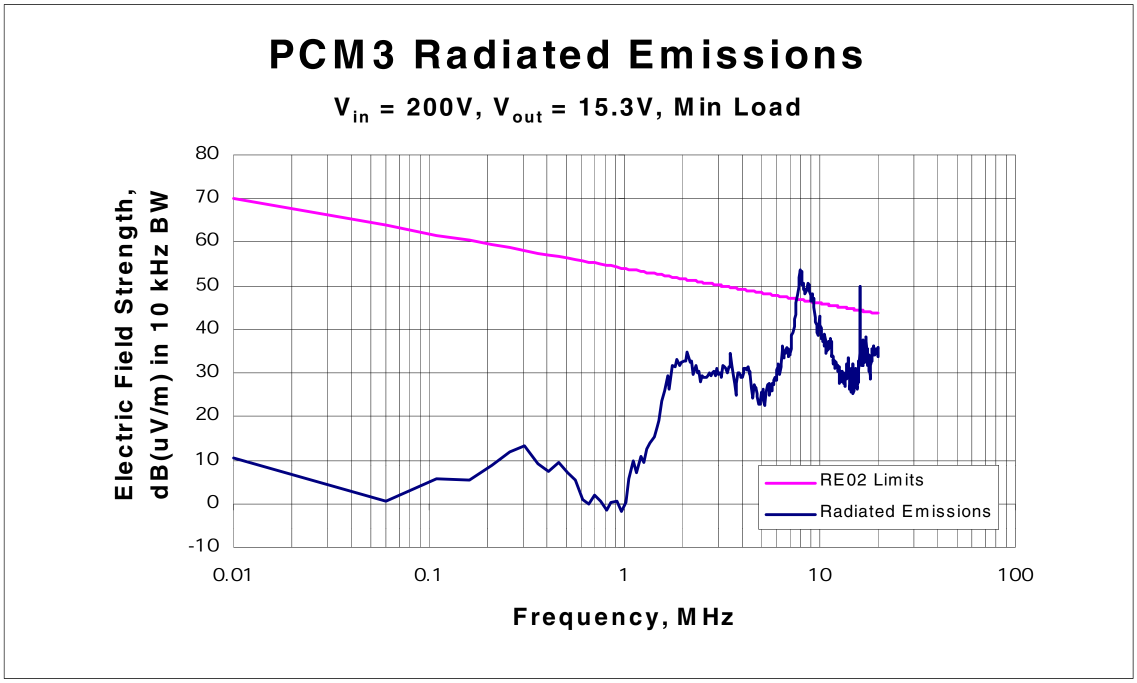

Figure 11. Radiated emissions: 200-V input, 15.3-V output, minimum load.

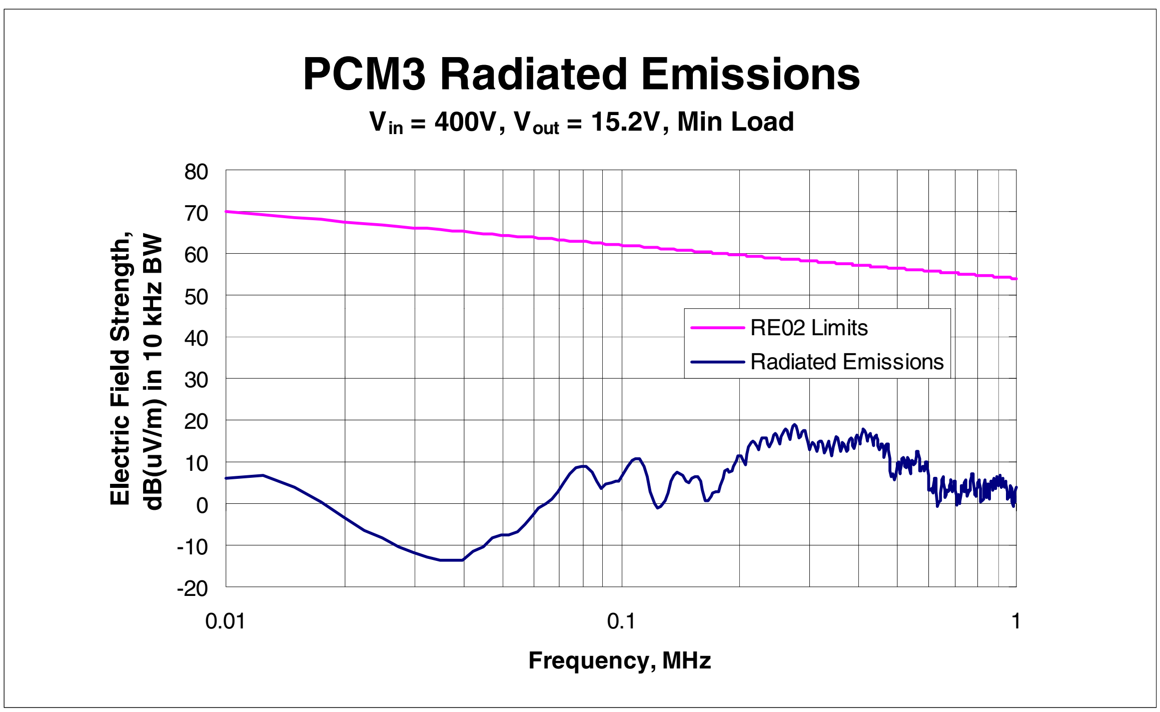

Figure 12. PCM-3 radiated emissions with 400-V input, 15.2-V output, minimum load.

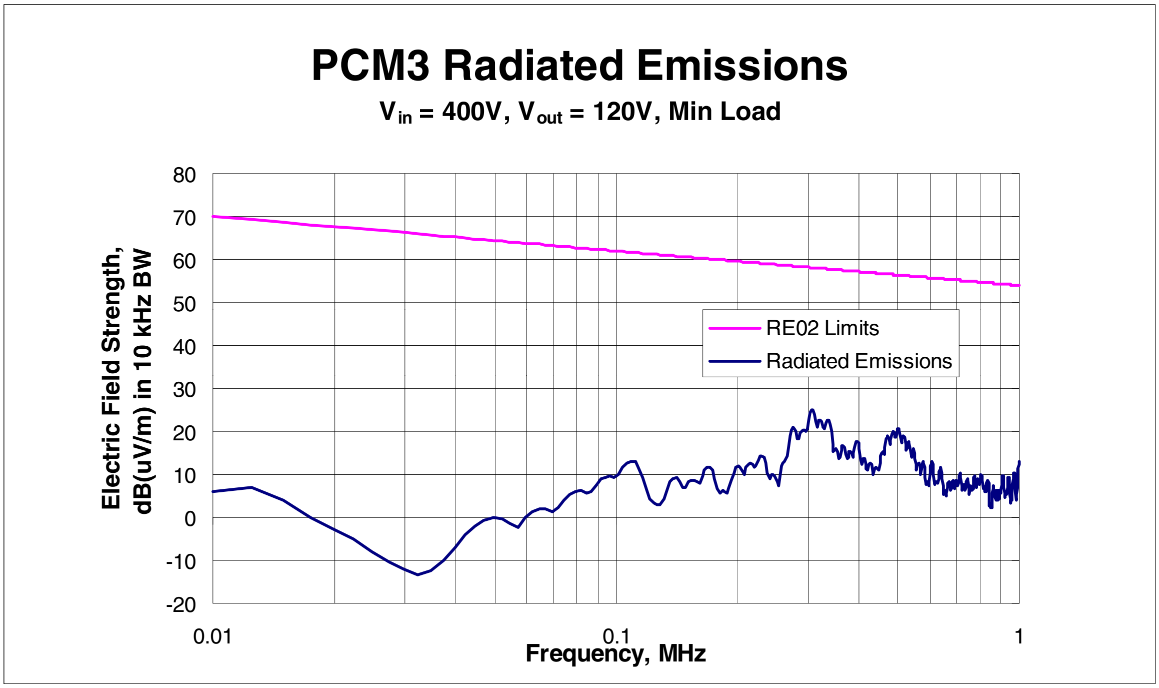

Figure 13. PCM-3 radiated emissions with 400-V input, 120-V output, minimum load.

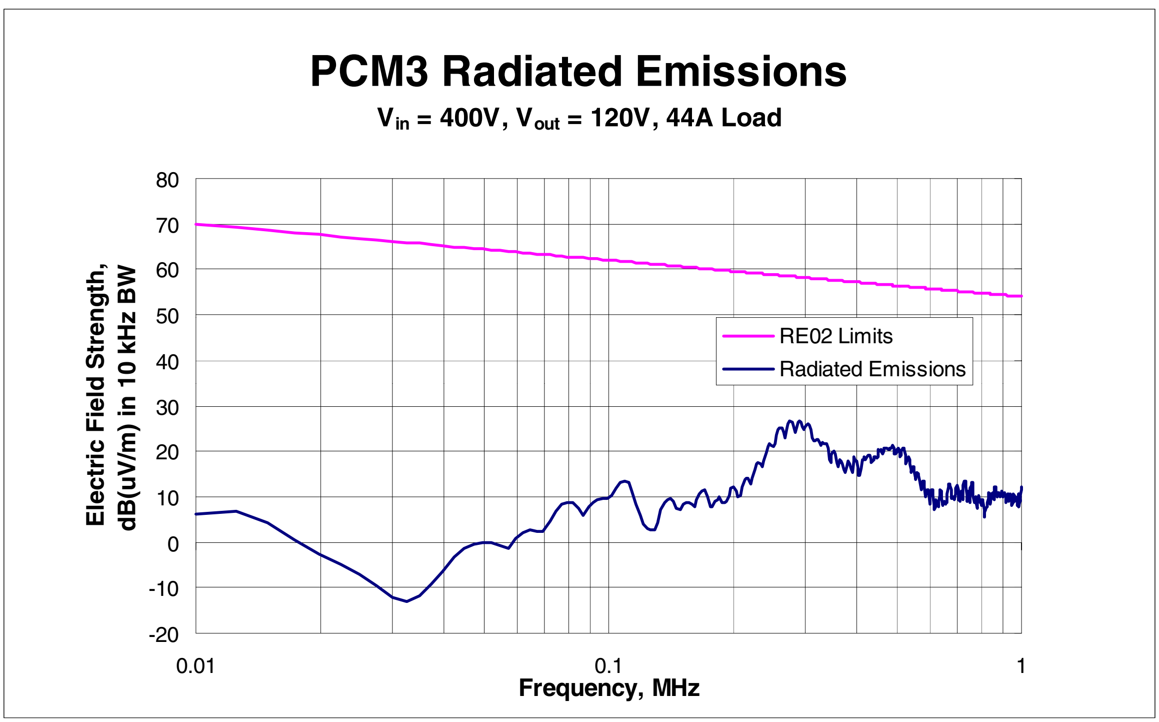

Figure 14. PCM-3 radiated emissions with 400-V input, 120-V output, 44A load.

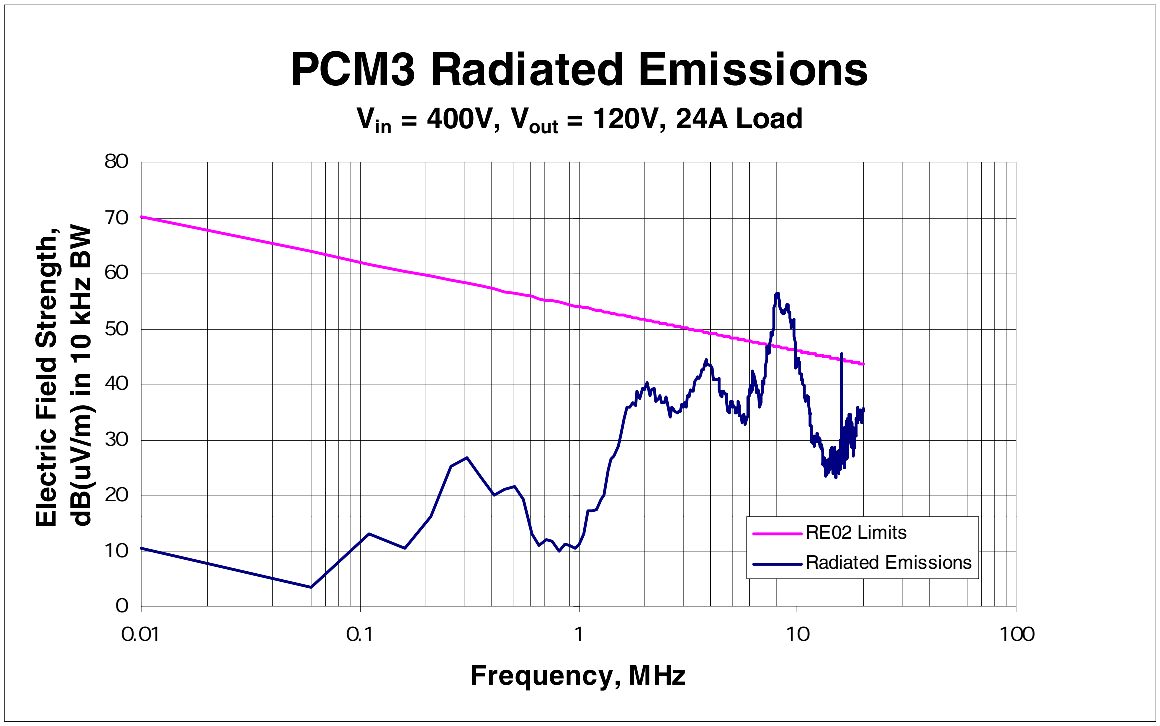

Figure 15. PCM-3 radiated emissions with 400-V input, 120-V output, 24A load.

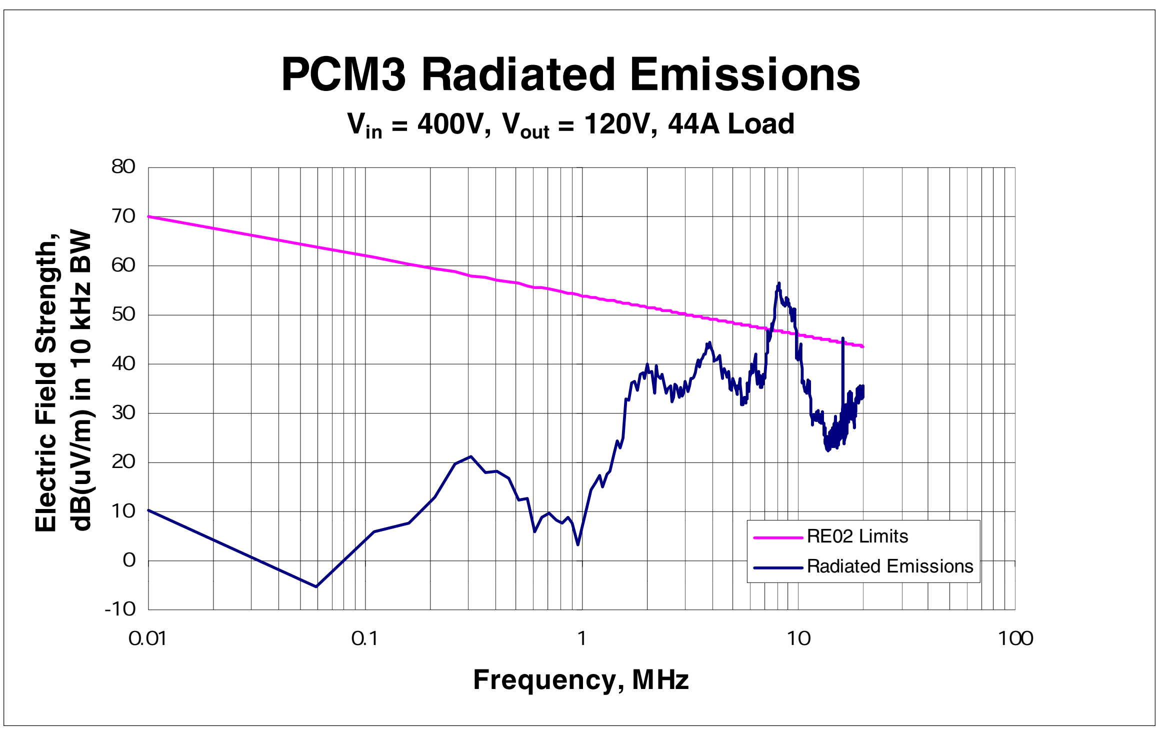

Figure 16. PCM-3 radiated emissions with 400-V input, 120-V output, 44A load.

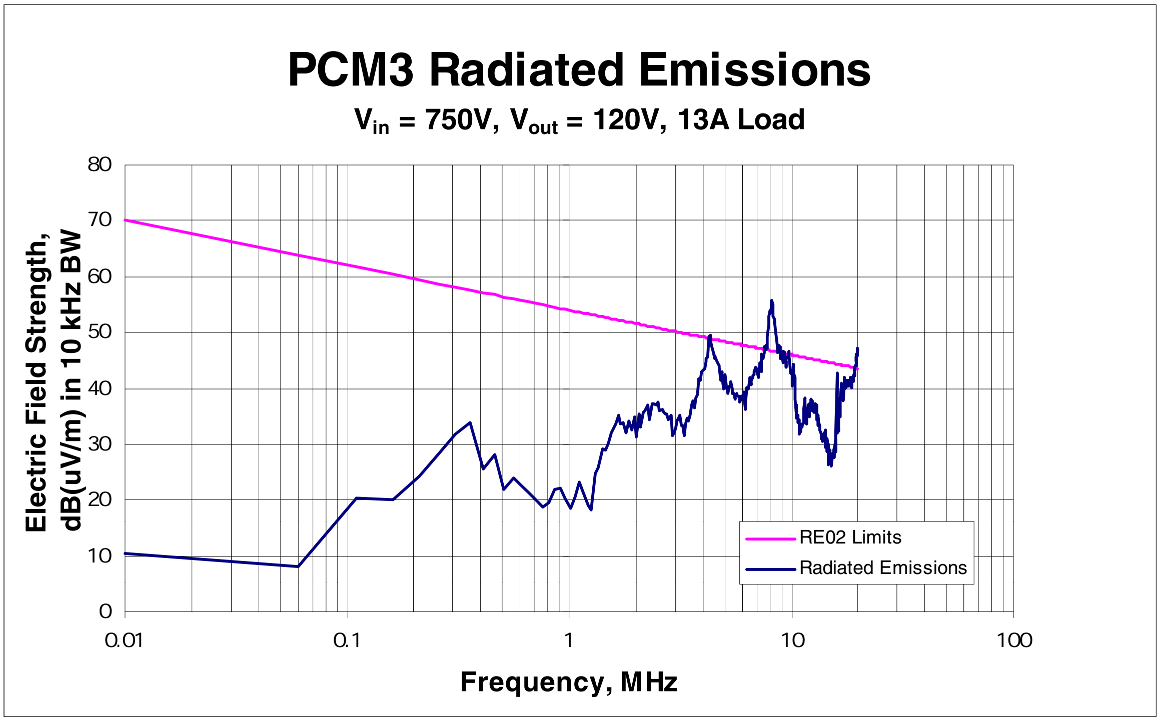

Figure 17. PCM-3 radiated emissions with 750-V input, 120-V output, 13A load.

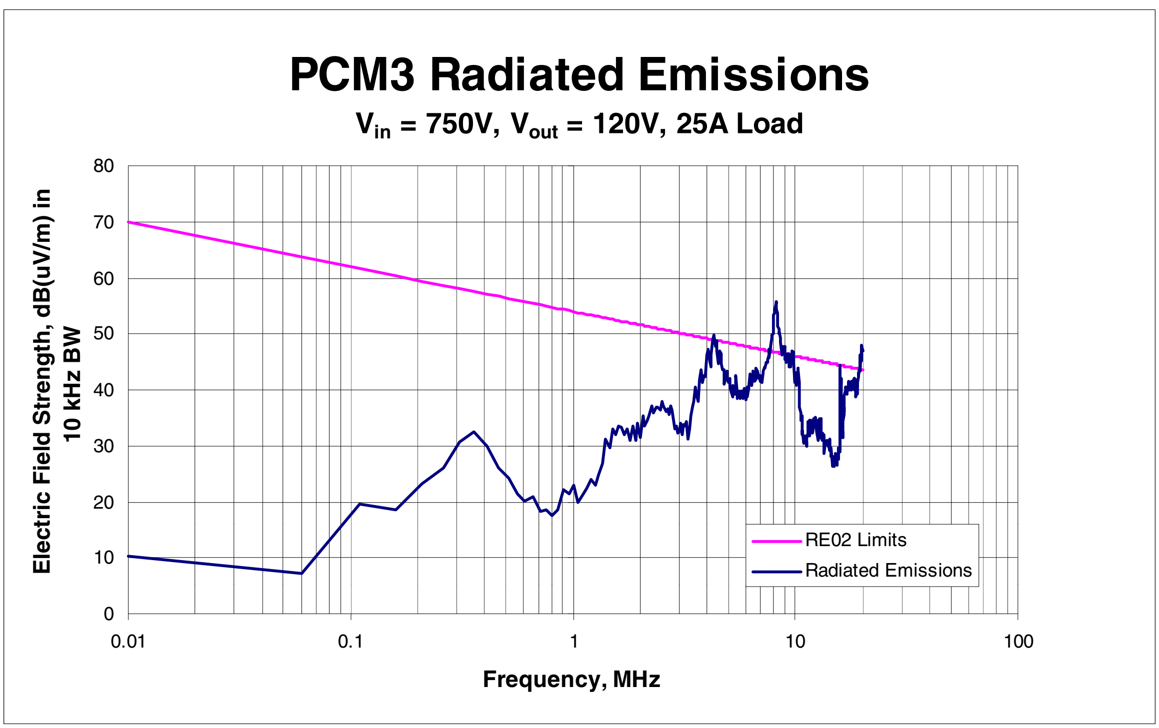

Figure 18. PCM-3 radiated emissions with 750-V input, 120-V output, 25A load.

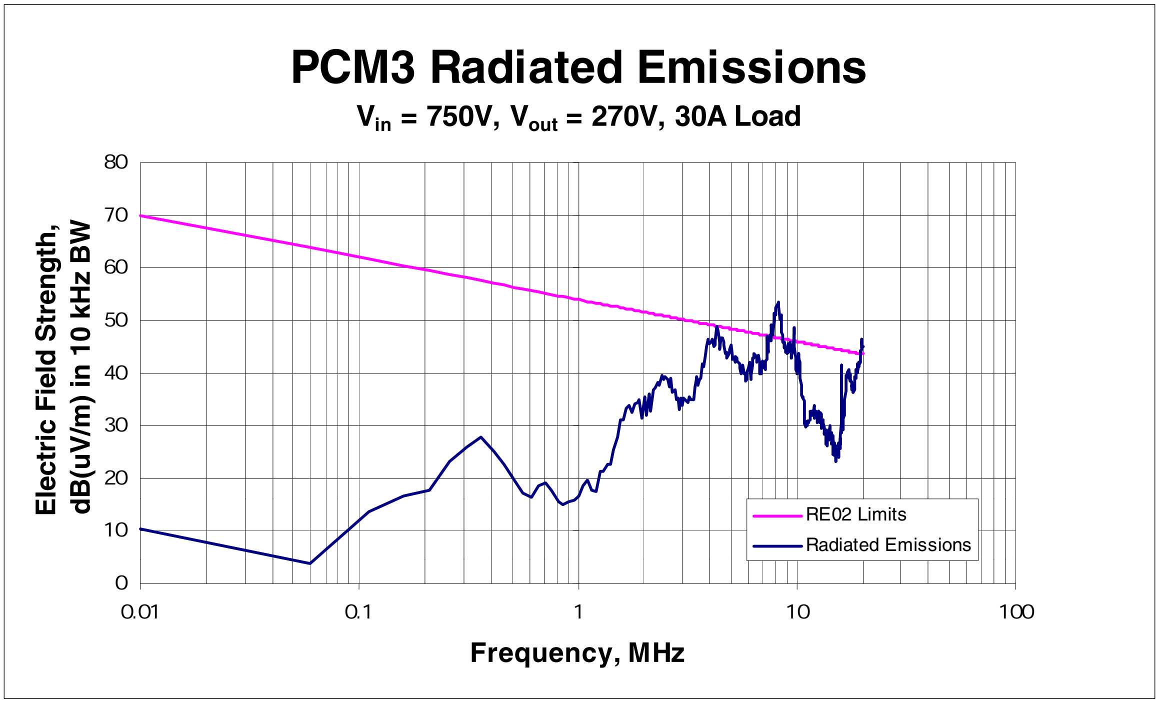

Figure 19. PCM-3 radiated emissions with 750-V input, 270-V output, 30A load.

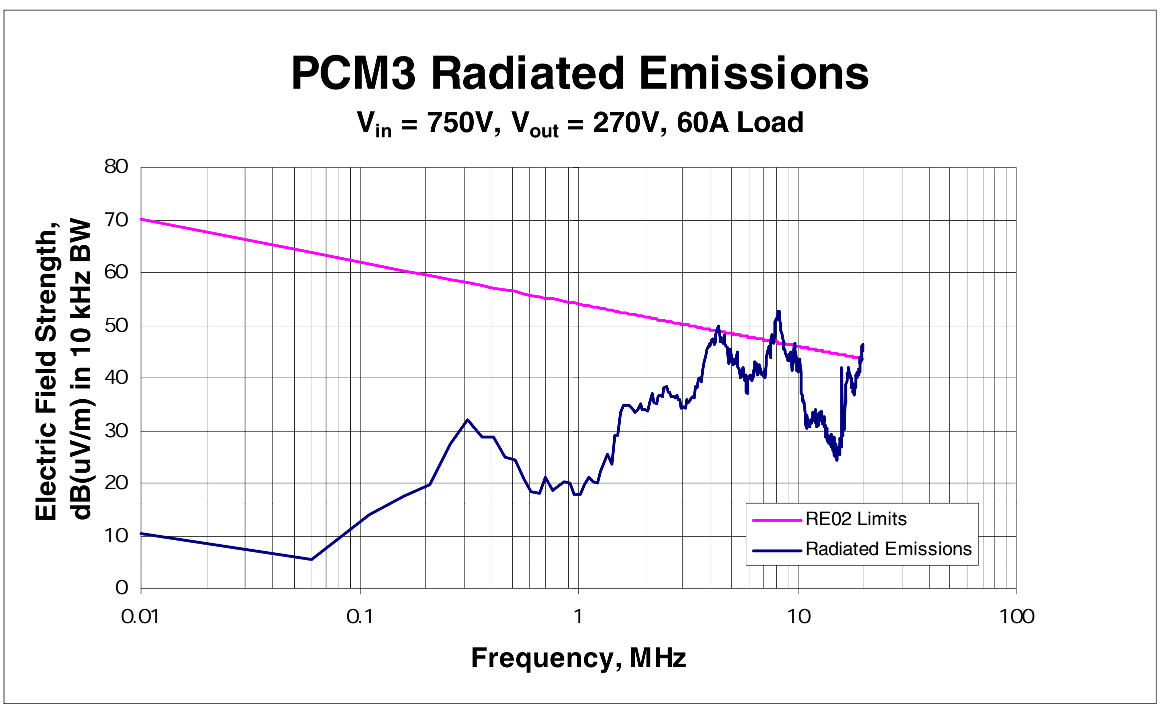

Figure 20. PCM-3 radiated emissions with 750-V input, 270-V output, 60A load.

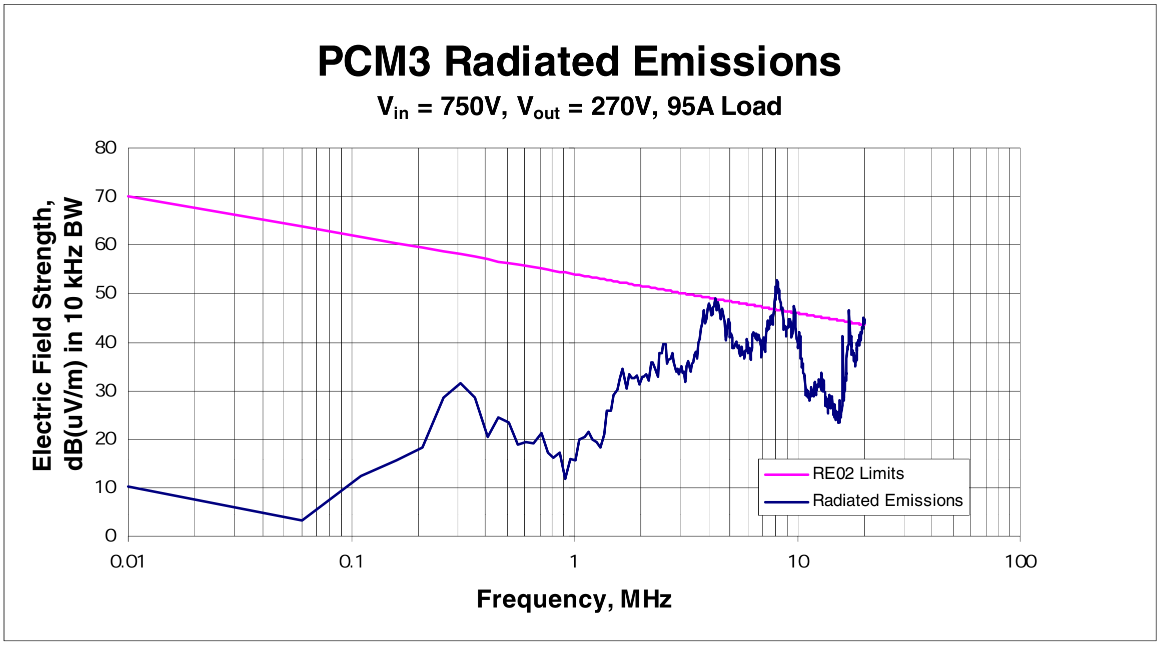

Figure 21. PCM-3 radiated emissions with 750-V input, 270-V output, 95A load.

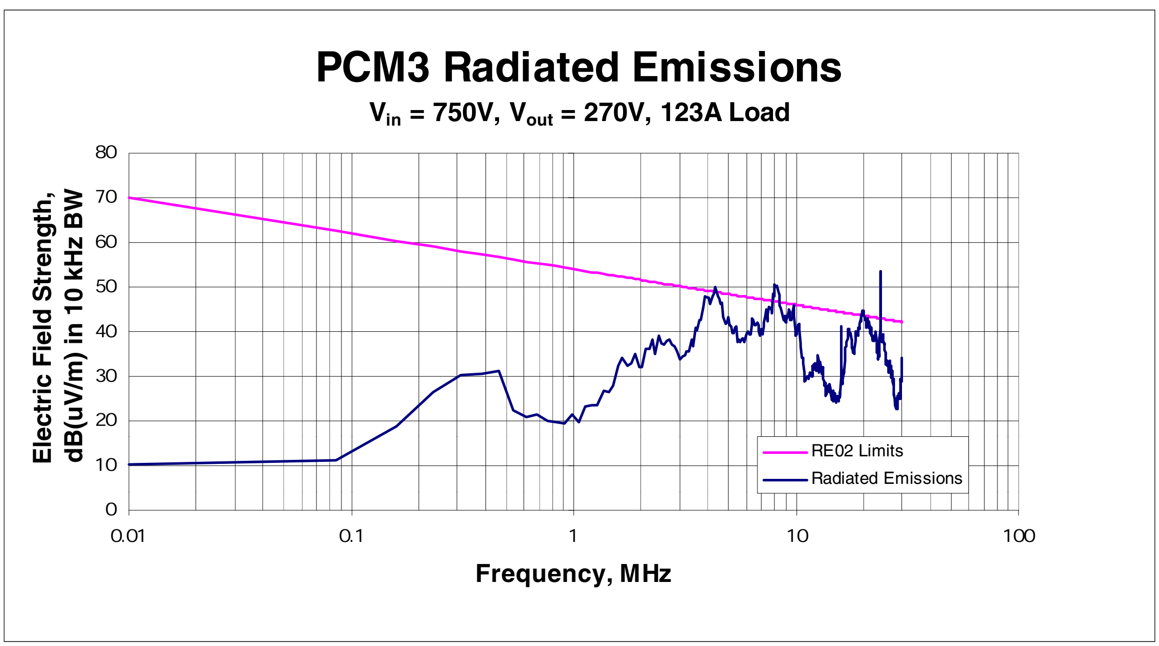

Figure 22. PCM-3 radiated emissions with 750-V input, 270-V output, 123A load.

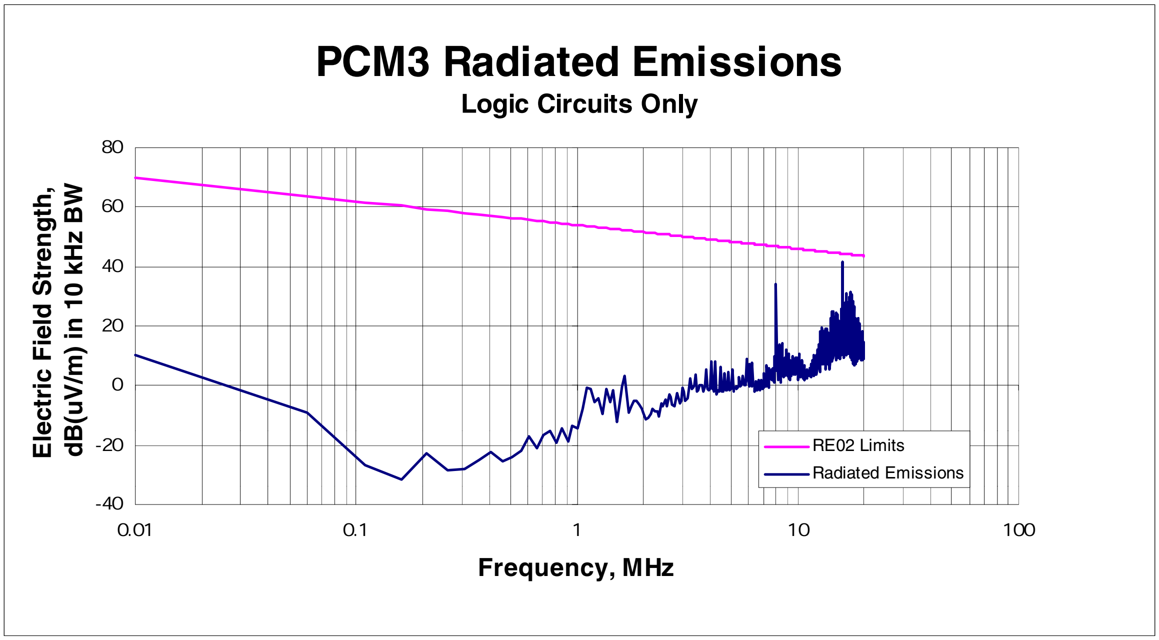

Figure 23. Radiated emissions of PCM-3 with logic circuits only operating.

COMPARISON TO RESULTS FROM SHIELDED ROOM TESTING

L3 Communications PSG duplicated one of the load conditions tested in SSC San Diego's GTEM measurements, and the logic-only condition, for radiated emissions measurements using a shielded enclosure. The electric field strength was measured in a 10-kHz bandwidth, as was used at SSC San Diego. Figure 24 shows the radiated emissions for the 95A load condition for the PSG and SSC San Diego measurements.

The general shape and trend of these curves match, but the magnitudes of the peaks do not. This may be caused by variations in the noise-like emissions of the PCM-3. The PSG shielded enclosure data were also obtained by subtracting a very high ambient level from the measurements. The ambient levels inside their shielded enclosure were higher than the limits allowed for radiated emissions in RE02.

Figure 25 shows the radiated emissions for only logic circuits operating. For both tests, the control circuitry was located outside the test enclosures, but the signal was carried inside on cabling. The length of two exposed cables inside the PSG enclosure was longer (about 10 feet) than in the SSC San Diego test (about 3 feet) and may explain some of the difference between the two measurements.

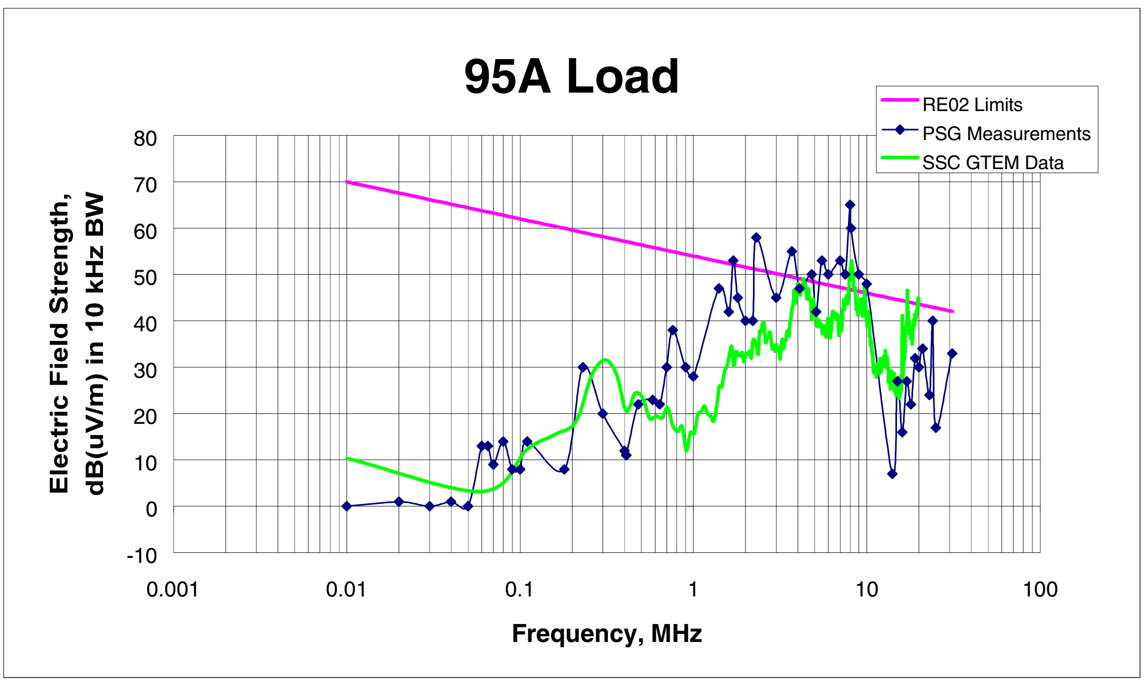

Figure 24. Comparison of GTEM and shielded enclosure radiated emissions measurements (PCM-3 at 95A load).

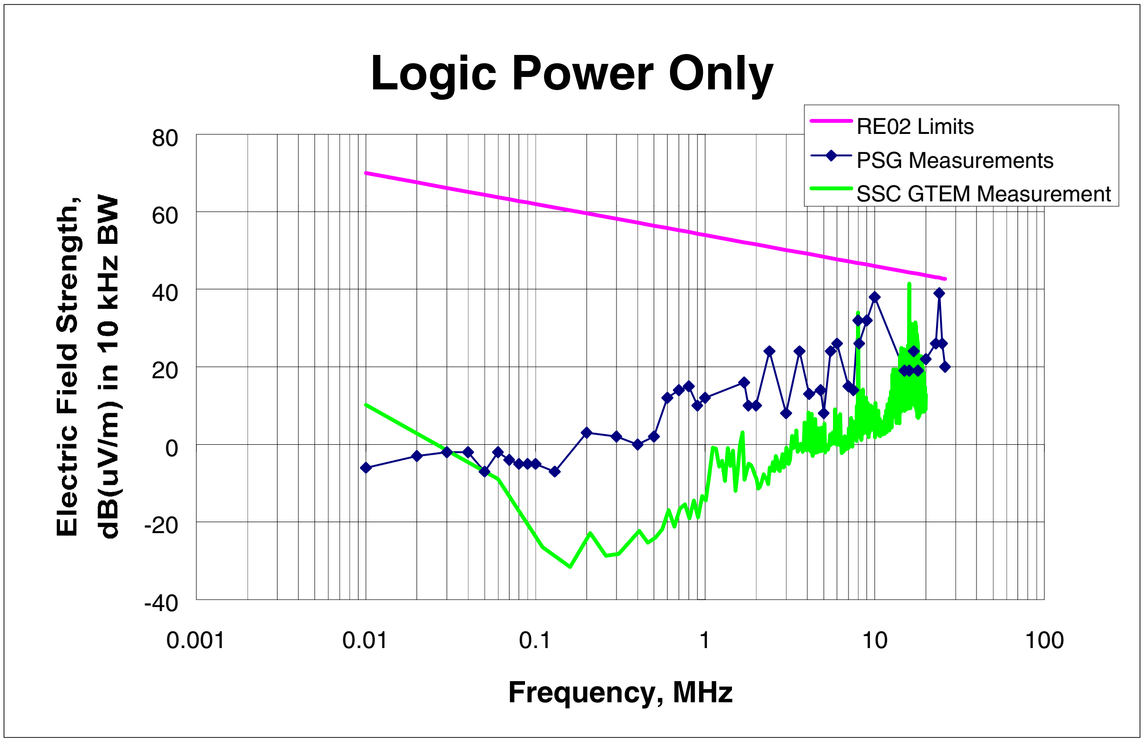

Figure 25. Comparison of GTEM and shielded enclosure radiated emissions measurements (PCM-3 logic only).

SUMMARY AND CONCLUSIONS

The GTEM measurement facility built by SSC San Diego was successfully used for the characterization of a soft-switching voltage converter for EMC considerations. The emissions of the L-3 Communications PSG PCM-3 unit were measured in the frequency domain. The measured data were processed to provide the electric field generated by the equipment under test.

The measured data show that the PCM-3 unit needs further shielding and packaging to meet MIL-STD-461D specifications for radiated emissions for frequencies between 1 and 30 MHz. Specifically, spikes caused by operation of the logic circuitry are of concern. In addition to having no shielding, this unit is an engineering prototype, and no EMI filters have been installed. MIL-STD-461D provides a benchmark against which future versions of the PCM-3 and PEBB units may be compared.

In terms of lessons learned, this effort showed the need to have a written agreement or contract in place with the owner of the equipment to be tested. L-3 Communications Corporation was much more responsive in providing equipment and technical assistance than other government sources of PEBB equipment, with whom only verbal agreements had been made. Such a written agreement or contract would also have prevented the need to change the test equipment because the exact operating parameters of the system would have been fixed in advance.

This set of measurements showed the efficiency of acquiring the EMI data using the GTEM cell. The data acquisition itself took about 1 minute per measurement. Most of the time involved in this effort was the setup of the PCM-3 voltage converter and the equipment that was needed to operate it. Because of the quickness of the data acquisition, this type of measurement is well-suited to heat-generating power electronics devices.

RECOMMENDATIONS

FOLLOW-ON MEASUREMENTS

The GTEM facility should be used to perform follow-on measurements of the PCM-3 radiated emissions in its future configurations. Follow-on measurements will show the affect of using PEBB switching devices in place of the commercial switches currently used, and will allow evaluation of whether the logic lines have been sufficiently shielded to reduce the spikes seen in this measurement.

SUSCEPTIBILITY MEASUREMENTS

The GTEM is a useful tool for measurement of EMI from power-generating equipment in radiated-emission-type tests. The GTEM can also generate electric fields for susceptibility tests but was not exercised in this mode for the PCM-3. This unit is still considered a prototype, and any changes to the shielding made in future design iterations could have a large effect on the unit's susceptibility. Because there is no backup or duplicate of this piece of equipment, and it is needed for other tests in the near future, susceptibility measurements would have been risky. In the future, GTEM data could be used to generate shielding requirements or to characterize a series of susceptibility tests that could determine the vulnerabilities of other equipment to the EMI generated by the power converter (figure 26).

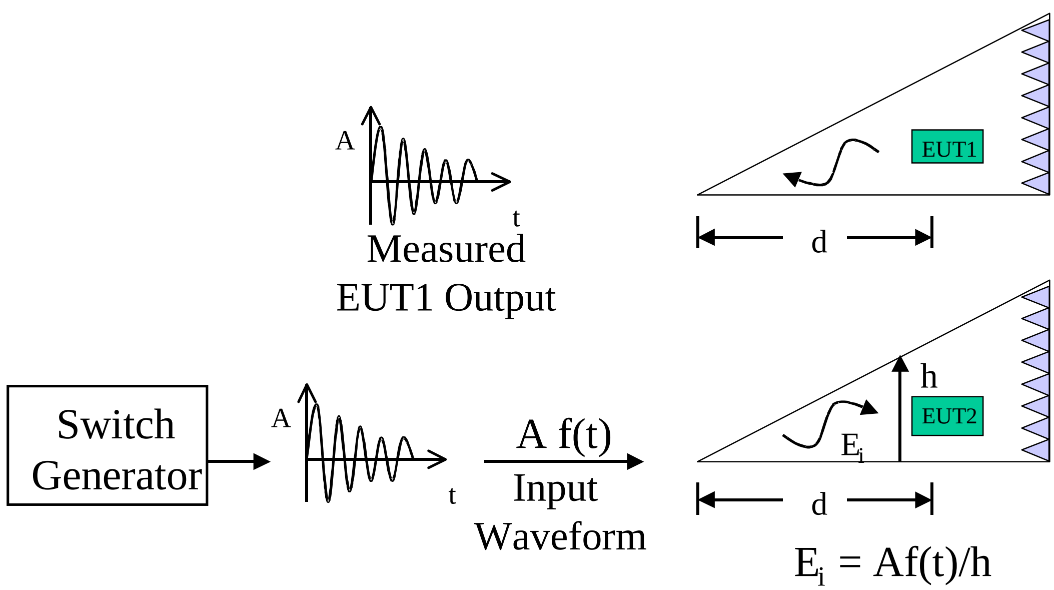

Figure 26. Susceptibility testing.

The waveform generated by switching events could be reproduced by the switching circuitry or other means and used as an input to the GTEM. The amplitude of the incident electric field generated in the GTEM would be defined at the location of the EUT and made equal to the electric field predicted at the location of the victim equipment. Because the measured electric field from EUT1 is a function of distance, *d*, an electric field at this location of any victim equipment relative to *d* can be determined. This electric field can then be replicated at the location of the victim equipment, EUT2, in figure 26. These tests would be very meaningful EMI tests because they would consider an actual predicted environment caused by a given equipment configuration instead of taking standard EMI measurements. The frequency versus amplitude plots required by standard EMI tests cannot produce this type of test data. The frequency versus amplitude data taken in standard EMI testing can also be provided by GTEM measurements using equipment such as spectrum analyzers. These data could be used to satisfy standard requirements. Susceptibility measurements should be performed when the equipment has been packaged in its final production form.

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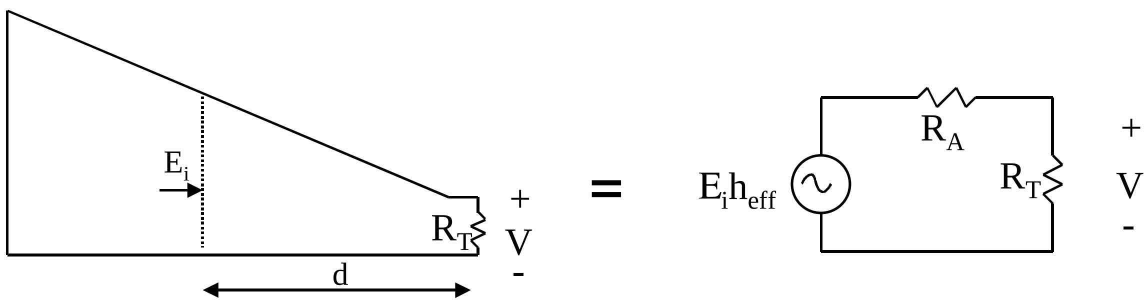
APPENDIX A
GTEM CELL TRANSFER FUNCTION

This appendix describes the derivation of a GTEM cell transfer function and how the transfer function is used for GTEM cell calibration.

DERIVATION OF TRANSFER FUNCTION

Figure A-1 shows the equivalent circuit of the GTEM cell.



E_i = GTEM electric field at location of EUT

R_A = resistance of GTEM cell

R_T = resistance of termination

h_{eff} = effective height of GTEM as an antenna

Figure A-1. GTEM equivalent circuit.

The measured voltage, *V*, across the terminating resistor, R_T, is related to the electric field by the effective height, h_{eff}, of the cell acting as an antenna. The equation for effective height of an antenna is given as follows (Krause, 1950):

$$h_{eff} = \sqrt{\frac{A_e (R_A + R_T)^2 + (X_A + X_T)^2}{120\pi R_T}} \ ,$$

where $R_A + jX_A$ is the impedance of the GTEM cell, $R_T + jX_T$ is the impedance of the termination, and A_e is the effective aperture. Because $X_A = X_T = 0$ and $R_A = R_T = 50\ \Omega$, this equation simplifies to

$$h_{eff} = \sqrt{\frac{100^2 A_e}{50(377)}}$$

$$h_{eff} = .73\sqrt{A_e}\ .$$

The effective aperture is defined as $G\lambda^2/4\pi$ so the effective height of the GTEM may be rewritten as

$$h_{eff} = .73\sqrt{\frac{G\lambda^2}{4\pi}} \,,$$

where G is the gain of the GTEM cell. The effective height simplifies to

$$h_{eff} = .206\lambda\sqrt{G} = \frac{61.8\sqrt{G}}{f_{MHz}} \,.$$

The generated voltage is divided between the cell's radiation resistance and the terminating resistance, R_T. The voltage measured at the GTEM output is therefore given by

$$V = E_i\, h_{eff}\, \frac{R_T}{R_T + R_A}$$

$$V = \frac{E_i\, h_{eff}}{2}$$

$$E_i = \frac{2V}{h_{eff}} = \frac{2\,V\,f_{MHz}}{61.8\sqrt{G}} = \frac{32\,V\,f_{GHz}}{\sqrt{G}} \,. \qquad \text{(A1)}$$

The gain of the GTEM cell is determined in the following section to have a value of 10.5. So, the transfer function may be rewritten as

$$E_i = 10V\,f_{GHz} \,. \qquad \text{(A2)}$$

GTEM CELL CALIBRATION

Figure A2 shows the setup used to calibrate the GTEM cell. A half-wave dipole antenna was placed inside the cell at a distance, *d*, from the feedpoint. The voltage at the feedpoint was measured for a power of 10 mW into the dipole. This procedure was repeated for three frequencies, using appropriately sized dipole antennas.

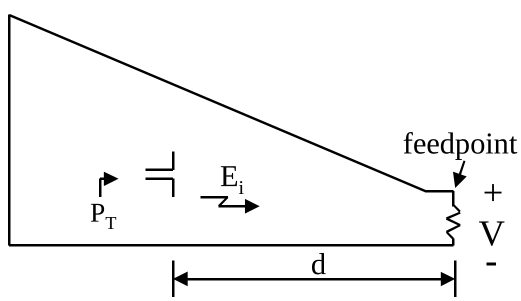


Figure A-2. Calibration of GTEM cell.

The radiated electric field from a half-wave dipole (or a quarter-wave monopole) driven by the power, $P_{T,}$ is given in the *Reference Data for Radio Engineers* (1975) as

$$E_i = \frac{\sqrt{49.2\, P_T}}{d}\,. \tag{A3}$$

To express the field inside the GTEM to that generated by a half-wave dipole, the field in equation (A1) is equated to the field in equation (A3). Solving for the measured voltage yields

$$V = \frac{\sqrt{49.2 P_T\, G}}{32\ d\ f_{GHz}} = \frac{.22\sqrt{P_T\, G}}{d\ f_{GHz}}\,. \tag{A4}$$

Equation (A4) allows the voltage received at the output of the GTEM to be related to the radiated power from a half wave dipole at a distance *d* from the apex (feedpoint) of the GTEM. This equation was used to calibrate the GTEM cell with half wave dipole antennas as shown in figure A-2. Table A-1 lists the measured results.

Table A-1. GTEM calibration measurement values.

Frequency (MHz)	Power Into Dipole (W)	Distance, d (Meters)	GTEM Power Out (dBm)	GTEM Output Voltage (V)
234	.01	4.87	-11.2	0.0614
464	.01	4.87	-17.1	0.0309
923	.01	4.87	-23.1	0.0156

The measured data points agree with the equations derived here for a GTEM gain of 10.5. The measured points have been superimposed on the bottom calibration line in figure A3, the equation for which is given by

$$P_{GTEM} = 10\log\left[\left(\frac{.7\sqrt{P_T}}{d\ f_{GHz}}\right)^2 \Big/ 50X10^{-3}\right]$$

where P_{GTEM} is in dBm, P_T is in watts, *d* is in meters, and f_{GHz} is in Gigahertz.

Figure A-3 is a graph showing the measured calibration points at 234, 464 and 923 MHz. The calibration line can be extrapolated to the lower frequencies by a 6 dB per octave slope. The bottom line represents the power at the output of the GTEM for a 10-mW input to a tuned dipole located 4.87 meters from the GTEM apex. Parallel lines have been drawn at 10-dB separations to show similar information for 100-mW and 1-W input power levels to obtain a complete calibration set. Equation (A4) shows the relationship between the output voltage at the apex of the GTEM to the power into a tuned dipole inside the GTEM located ***d*** meters from the apex. Equation (A4) was obtained by equating the electric field generated by a tuned dipole to the GTEM electric field transfer function to find the output voltage produced at the GTEM apex.

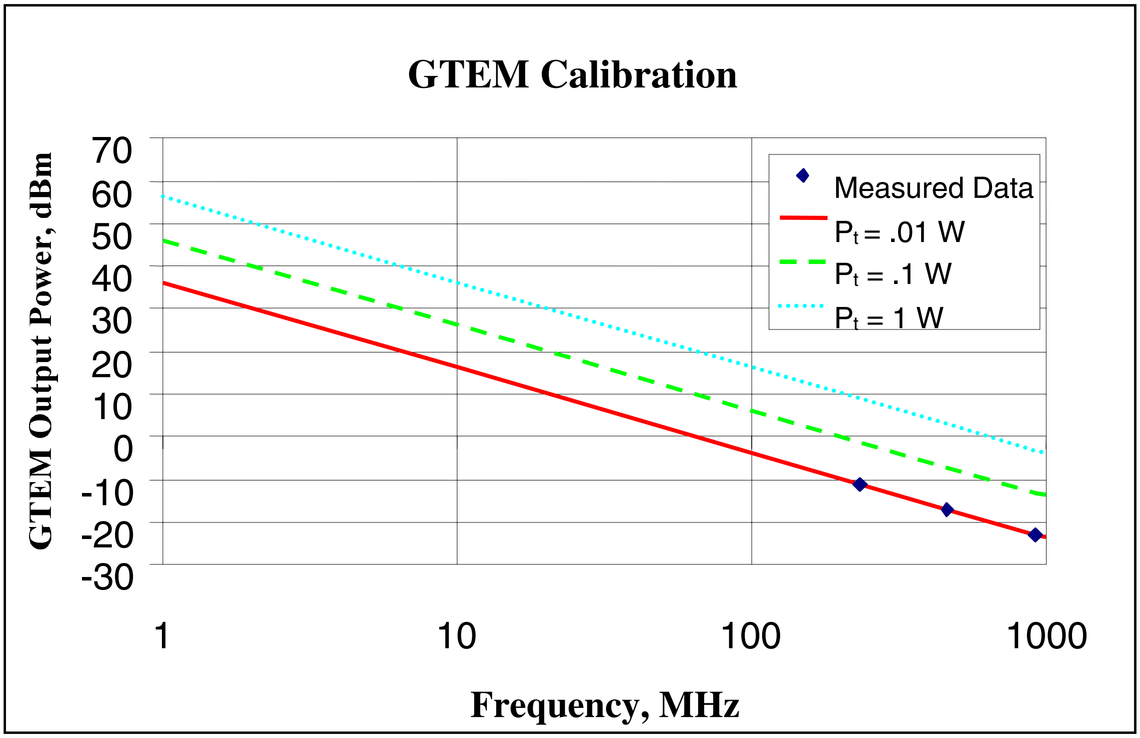


Figure A-3. Calibration data relating GTEM output power to power into dipole.

APPENDIX A
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